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Review on Biochar for Enhancing Biogas Production from Anaerobic Digestion of Food Waste

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Abstract

Food waste is the major waste fraction in municipal solid waste and is indeed a significant issue in society, with substantial economic, environmental, and social impacts. Various technologies exist to manage food waste, including animal feeding, anaerobic digestion, composting, incineration, and landfilling. Among these technologies, anaerobic digestion is the most recognized, efficient, and sustainable method. It can produce biogas and nutrient-rich fertilizer simultaneously. Because of the high organic load of food waste and the presence of mass nutrients, it is a suitable substrate for the anaerobic digestion process. However, the anaerobic digestion process faces challenges such as process instability, slow rate of biogas generation, and sudden failure of biogas generation due to susceptibility to inhibitors. All these challenges have affected its efficiency. Biochar has been identified as a promising alternative to address most of the drawbacks in the anaerobic digestion process and enhance methane production. Biochar is a carbon-rich material produced through thermochemical conversion processes. Because of its specific properties, such as its high specific surface area, porous structure, adsorption capacity, buffering capacity, and a higher number of functional groups, it has the potential to enhance biogas production in anaerobic digestion processes. Biochar exhibits pH buffering properties, enhances the enrichment of functional microbes, alleviates the effects of inhibitors, and accelerates the process of direct interspecies electron transfer. This paper reviews the effectiveness of biochar as an additive in the anaerobic digestion process of food waste. It further examines the properties of biochar, the factors influencing these properties, and the mechanisms through which biochar enhances the AD process.

Keywords: Biochar; Anaerobic Digestion; Food waste; Biogas; Enhancement

1 Introduction

Food waste is one of a major waste stream in municipal solid waste. Approximately one-third of all food produced for human consumption worldwide is either lost or wasted. It equal to 1.3 billion tons of food per year [1]. So, food waste is indeed a serious issue in society, with significant economic, environmental and social implications. The impact of food waste is considerably high and it contributes to the climate change due to the emission of greenhouse gases. Food waste can be occurred in all stages of food supply chain. Such as; production, transportation and usage. The main categories of food waste are dairy, meat and poultry, fish, fruit and vegetable, bakery, brewing and winery industry and others.

There are several technologies to treat food waste. They are animal feeding, anaerobic digestion, composting, incineration and landfilling. Among these five methods, most common and efficient method is anaerobic digestion. Anaerobic digestion (AD) can be used to obtain biogas and simultaneously nutrient rich fertilizer. Converting food waste into nonrenewable energy become more effective and sustainable solution when considering the rapidly increasing cost of energy supply, waste disposal and public concerns regarding environmental problems.

Due to the high organic load of the food and the presence of mass nutrients, food waste is more suitable substrate in bio gas generation through AD. Researchers found that if all the food waste in United State was treated by AD, the generated power equal to 10 million households annual electricity consumption [2]. So, Bioenergy based food waste management through AD can be considered as an effective solution for both energy crisis and waste management.

Anaerobic digestion is a biological process of organic substrate decomposition in the presence of several species of bacteria under controlled environmental conditions in the absence of oxygen. In this process micro-organisms release series of metabolites and breakdown the organic materials to produce methane (CH_4) and carbon dioxide (CO_2). AD is a complex process and there are four key biochemical reactions. They are Hydrolysis, Acidogenesis, Acetogenesis and Methanogenesis. Though they are synergistically operates, there are particular issues related to the anaerobic digestion of food waste including, low methane yield, unstable operation due to pH value fluctuations, presence of Inhibitory accumulation of intermediate products (eg: volatile fatty acids (VFAs)) [3]. Mitigation of so-called barriers in food waste anaerobic digestion is a keen interest in the current days and there are several researches are going on this area.

Biochar is a carbon rich material, which can be produced via restructuring or incomplete oxidation during thermochemical conversion process. Biochar can be produced from a variety of biomass, such as; wood, crop residues, dairy manure and wastewater sludge etc. Due to the high porosity, large specific surface area, good electrical conductivity, excellent ion exchange capacity, abundant surface functional groups, several functional groups and remarkable buffering capacity the biochar can be enhanced the anaerobic digestion process. Lag phase of methanogenesis process is reduced by adding biochar. Not only that, but also it can mitigate toxic inhibition, immobilize functional microbes and accelerate electron transferring between methanogenesis and acetogenic microbes [4]. Therefore, this study is to review the biogas enhancing through bio char in food waste anaerobic digestion. Additionally, this review aims to explain how biochar enhances anaerobic digestion, and identify factors influencing its efficacy. The synthesis of this information provides insights into the current state of research, identifies gaps in knowledge, and suggests future directions for further investigation. This comprehensive synthesis provides a clear understanding of current research trends, highlights gaps in knowledge, and proposes future avenues for further investigation.

2 Literature Review

2.1 Food Waste

Food waste (FW) could be collected in any stage of food supply chain. They can be categorized such as from initial production stage, transportation to final household consumption. As an average, globally, 23.7 million tons of food is produced daily [5]. In developed and developing countries the amount of FW generating is about 107 and 56 kg/capita/year respectively [5]. Food waste can be categorized as household and industry. Figure 1 shows the FW gene ration of European union and household food waste generation has been counted as, approximately 53% of the total FW [5]. The Asian countries also produce a huge amount of FW. In 2012, the FW production was equal to the per capita as high as 0.45 kg/d in South East Asia [6]. Due to global urbanization and population expansion, FW now makes up around 32-62% of MSW and is expected to increase [7].

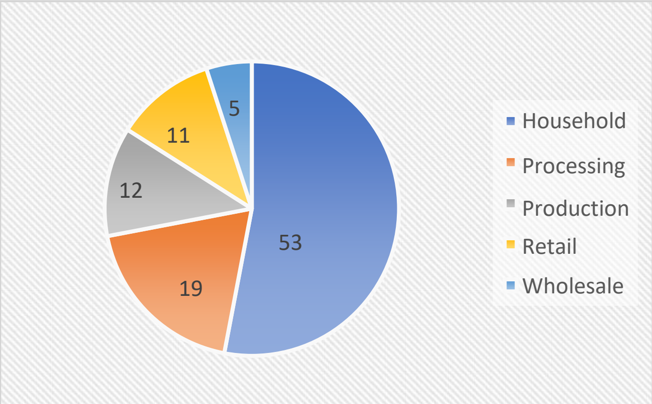

Figure 1 Food Waste Generation of European Union [5]

Mainly, there are five treatment methods to handle the food waste. They are animal feeding, anaerobic digestion, composting, incineration and landfilling. Most of the food waste, 95% of total is end up with landfills and this may cause to the greenhouse gas emission [5]. Food waste landfills have a significant impact to the global climate change [2]. A large volume of methane and carbon dioxide is emitted from the food waste landfills. Methane has much stronger warming effect compared to the carbon dioxide by about 20-25 times [2]. Due to the population growth and the urban areas expand, finding a suitable space for landfill also becomes a challenge. Additionally, landfilling has negative aesthetic impact on surrounding areas and effects to the quality of life for nearby residents. In landfills, the release of toxic substances from the food waste including chemicals that can contaminate water resources and food chain. This may lead to the long-term health problems [5].

Incineration of food waste is also a widely practiced method, but it comes with significant drawbacks. Due to the high-water content (70%-90%) of food waste and the air pollutants generated during the incineration process, this approach is not sustainable [7]. Further, incineration required high cost and it is energy intensive.

Composting is the most commonly used method for food waste. In composting, microbes are metabolized organic waste material and reduce its volume by as much as 50 percent [5]. When food waste composting is widely practiced, gaseous emissions, odor issues and nonbiodegradable impurities have been identified as the main challenges [8].

Another food waste management technique, called anaerobic digestion (AD), is used to recycle FW and create biogas, which contains a mixture of gases such as methane (CH_4) and carbon dioxide (CO_2) [8]. The biogas can serve as a direct substitute for natural gas, offering an alternative solution to meet the global energy crisis [5] Therefore, compared to the other processes, the AD process is an efficient and sustainable alternative for managing FW and is used extensively worldwide.

2.2 Anaerobic Digestion Process

Anaerobic digestion is a biological process that breaks down organic materials in the presence of several species of microorganisms mainly bacteria under the controlled environmental conditions in the absence of oxygen. Through the AD, organic matters that contains in food waste can be converted into biogas. The byproduct of AD which is called digestate can be used as a fertilizer. There are four key biological and chemical stages in anaerobic digestion process. As shown in Figure 2 it includes hydrolysis, two acid forming stages (Acidogenesis and Acetogenesis) and methanogenesis.

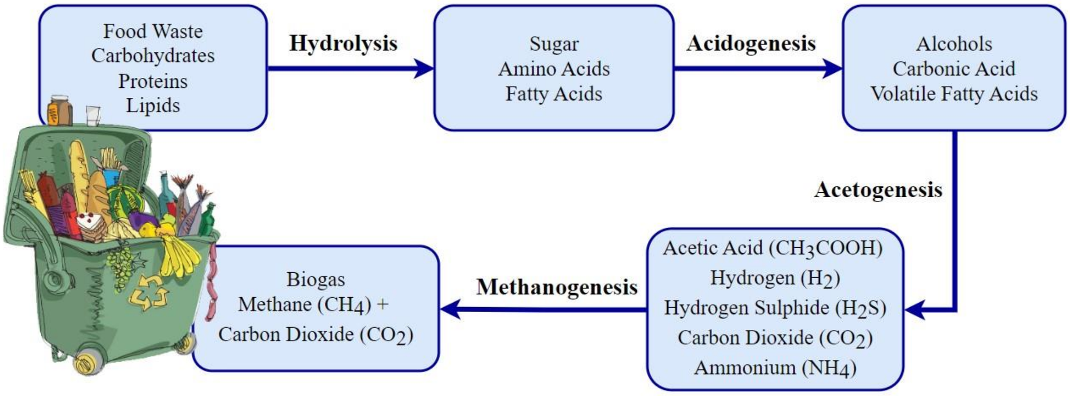

Figure 2 Key Stages of Anaerobic Digestion Process [5]

Hydrolysis is the first stage of anaerobic digestion. In this stage the organic compounds of food waste including carbohydrates, proteins and lipids are hydrolyzed into smaller units such as sugar, amino acids and fatty acids respectively through extracellular enzymatic activity. In Acidogenesis stage, acidogenic bacteria convert the smaller units produced during the hydrolysis into volatile fatty acids (VFAs), alcohols and ammonia. The VFAs produced in previous stage converted into acetic acid, hydrogen and carbon dioxide through acetogenesis process. Methanogenesis is the final stage of an anaerobic digestion process and the products of previous stage are utilized by the microorganisms to convert them into methane (CH_4) and carbon dioxide (CO_2).

2.3 Factors Effected to the Anaerobic Digestion of Food Waste

Numerous factors affect the microbial metabolism in anaerobic digestion. Therefore, these parameters must be considered and carefully control during practical implementation. Table 1 shows some relevant parameters and their optimal conditions in hydrolysis, acetogenesis and methanogenesis processes [9]. Further, the Composition of the food waste and loading rate also effect to the Anaerobic Digestion process.

Table 1 Parameters effected to the AD Process [9]

Parameter	Hydrolysis/Acidogenesis	Methanogenesis
Temperature	25-35 °C	Mesophilic: 30-40 °C Thermophilic: 50-60 °C
pH	5.2-6.3	6.7-7.5
C:N ratio	10-45	20-30
Redox Potential	+400 to -300 mV	Less than -250 mV
Trace Element	No special requirements	Essential: Ni, Co, Mo, Se

2.3.1 Temperature

The operating temperature plays a major role in anerobic digestion of food waste. The AD can be classified according to the operating temperature such as; mesophilic or thermophilic process [10]. According to the reported experimental results, methane production yield is high at the thermophilic process [11]. Figure 3 shows that, compared to mesophilic digestion, thermophilic conditions provide higher gas production within the optimum pH range (6.7-7.5) of methanogenesis process.

2.3.2 pH

The growth of the bacteria and the methane production are inhibited in acidic environment [11]. Table 1 shows that different stages of digestion have specific pH requirements, and maintaining the appropriate pH range ensures efficient degradation of organic matter and methane production. The simulate optimal values of pH at mesophilic and thermophilic temperatures are shown in Figure 3. According to Figure 3, the cumulative methane production is high in optimum pH range from 7 to 7.5 pH values.

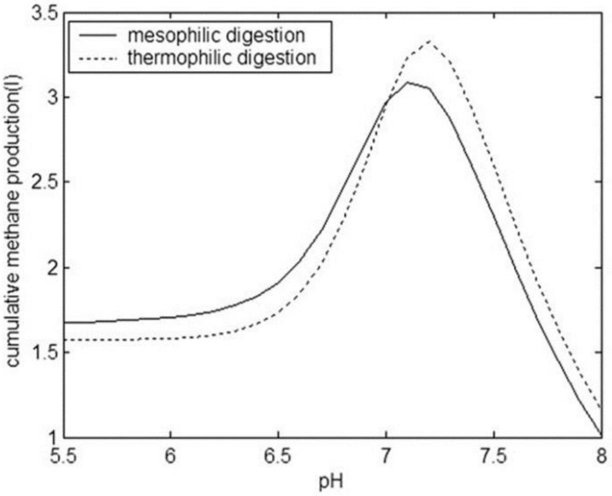

Figure 3 Simulated optimal values of pH at different temperatures [12]

2.3.3 Composition of the Food Waste (C:N ratio)

The performance of anaerobic digestion can be affected by the properties of the substrate, such as its organic content, nutritional composition, C:N ratio and biodegradability. Because of the different bio-chemical properties of the protein, lipids, carbohydrates, and cellulose components in the food waste, the bio-methanization potential of the waste can be depends on these components [11]. The organic content of the food waste typically measured as total solids (TS) or volatile solids (VS). Food waste with higher organic load tends to have higher biogas yield. The highest methane yields given by the systems with excess of lipids, but the retention time also high. When the system with high protein content, the methanization is faster. There are adverse impacts also occurred when having excess amount of lipids and proteins. The inhibitory effects have been observed due to the VFAs and ammonium nitrogen accumulation [11]. VFAs can inhibit digestion at concentrations above 10,000 mg/L[9]. The optimum C:N ratio is 20-30:1for anaerobic digestion process [9]. If the ratio is higher than the 30, growth of microorganisms are slow down. In 2012, D. and Grilc identified that this is because of the insufficient protein. If the C:N ratio is lower such as 3:1, growth of microorganism still occurred but there is a risk for ammonia inhibition [9].

2.3.4 Redox Potential

Low redox potential is required for efficient anaerobic digestion process [9]. The optimum conditions are mentioned in Table 1. The oxidizing agents should not be added to the digester to exist the optimum range of redox potential. Oxygen, sulphate, nitrate and nitrite are some examples for oxidation agents[9].

2.3.5 Trace Elements

Inorganic salts like sodium, can inhibit anaerobic digestion. If the substrate contains high salt concentrations as 3000 mg/L, sodium inhibition may be occurred [13]. But the AD can be operated up to the concentration of -16,000 mg/l of sodium[9]. To avoid this effect, high salt substrates can be pretreated. And also, alternative neutralizing agents can be used. In low concentrations of heavy metals such as lead, cadmium, copper, zinc, nickel, and chromium can promote anaerobic digestion, but, at high concentrations, they become poisonous. Nonspecific inhibition can also be driven on by other organic agents such antibiotics, herbicides, insecticides, disinfectants, and surfactants. Due to the toxicity of these organic substances biogas production can be reduced by 70%[9]. Further, substances required for the anaerobic digestion process can be inhibitory at higher concentrations of VFAs [9]. VFAs are essential for AD process but at concentrations above 10,000 mg/L, VFAs can inhibit digestion and acts as trace element [9].

2.4 Issues Related to the Anaerobic Digestion Process

They have found that though AD is widely applied technology, this process still undergoes technical, economic and social challenges. The efficiency and stability of the AD process is affected by inhibitors. Inhibitors can be classified as direct source and indirect source[14]. Direct inhibitors are present in the feedstock and indirect inhibitors are the intermediates which are generated during the AD process. In some studies it has been identified that, high degradability create acidic nature of the digester causing to the instability of the overall process of AD due to decreasing the pH of the digester, inhibiting methanogenic microorganisms and causing process instability [15].

2.5 Role of Biochar in Anaerobic Digestion Process

Biochar is a carbon rich material, which can be produced via restructuring or incomplete oxidation during thermochemical conversion processes at a temperature range of 300-950 ^{o}C [7]. Biochar can be produced from a variety of biomass, such as; wood, crop residues, dairy manure and waste water sludge. Biochar yield and its properties depend on the various factors including feedstock, the method that used to produce biochar (pyrolysis, gasification and hydrothermal process) and the operation conditions.

Then, the properties of biochar and biogas enhancing mechanism in the digester is discussed in detail below.

Biochar has a porous structure, providing a large surface area for microbial colonization. This increased surface area allows for more efficient attachment and growth of methanogenesis microorganisms. Therefore, degradation of organic matter is promoting. So, the overall anaerobic digestion process could be enhanced.

Specific Surface Area (SSA) of biochar is also one of the key factors along with the other properties in the adsorption of environmental contaminants. The high SSA of biochar provide more effective interaction with the surrounding species [16]. The surface area and the pore volume is highly dependent of the operational conditions of the thermochemical process[17].

Essential nutrients and trace elements are important for the growth and activity of methanogenic microorganisms. The surface functional groups on the biochar play another role in adsorbing metals [18]. Biochar has the various functional groups including hydroxyl (-O-H), aliphatic carbon (-C-H), Carbonyl (-C=O), amino groups (-N-H). These functional groups can act as binding sites for these nutrients and trace elements. With more functional groups, biochar could provide a favorable environment and essential nutrient supply.

Generally, all the biochar contains bulk elements such as carbon, hydrogen, oxygen. And also, it consists of heteroatoms and metal elements [19]. These elements are correlated with the functional groups. Moreover, biochar has both positively and negatively charged functional groups. Colonization of microorganism is increased due to the high surface area and porous structure of the biochar. Methane yield can be increased with the help of surface functional groups and the electrical conductivity of biochar [7].

Biochar exhibits good electrical conductivity, which can facilitate electron transfer during the AD process. This electron transfer is beneficial because it can enhance the methanogenesis process, where microorganisms produce methane. By improving electron transfer, biochar helps microorganisms more efficiently convert food waste compounds into biogas, thus promoting the overall biogas production process.

Biochar has buffering capacity and addition of biochar can increase the alkalinity and the pH value of system. The biochar has a pH range of 3-12 and this may help to reduce the ammonia inhibition and acid stress environment in the AD process [20].

High organic loading contributes to form a complex pore structure. The carbon rich biomass has a potential to give higher biochar production yield. Due to the high organic content, the plant base type of biochar has an ability to improve its adsorption and immobilization [21]. And also, the feedstocks types are affected to the electron transferring of biochar[22]. Table 2 shows various types of biochar that produced by using different feedstock types along with their respective properties such as particle size, surface area, electron donating and accepting capacities.

Table 2 Properties of Different Types of Biochar [21]

Acronym	**Wheat bran**	**Wood**	**Orchard**
Original Feedstock	Wheat bran pellets	Coppiced woodlands	Orchard pruning
Pyrolysis Temperature (^oC)	800	500	500
Particle size (mm)	1.7-2	1.7-2	1.7-2
BET specific surface area (m^2/g)	55 ± 1	61 ± 1	13.7 ± 0.5
Electrical Conductivity(S/m)	49.9	1.6	0.5
The pore volume (cm^3/g)	0.0445	0.0483	0.0165
Electron donating capacity (meq/g)	0.055 ±0.01	0.199 ±0.02	0.298 ±0.02
Electron accepting capacity (meq/g)	0.434 ±0.05	0.104 ±0.01	0.404 ±0.01

Pyrolysis temperature is a critical parameter that significantly effected to the properties of biochar. The temperature at which pyrolysis is carried out influences the chemical composition, physical characteristics and potential applications of the resulting biochar. When pyrolysis temperature increase, this may lead to loss of the organic functional groups such as carboxyl and alcohol groups, and an enrichment of alkaline minerals in the biochar [18]. Not only the functional groups, SSA, one of the main factors of adsorption is affected by the pyrolyzing temperature. In 2020, Hopkins & Hawboldt reported in the literature, that there is a positive correlation between temperature and surface area up to 600°C and beyond which the specific surface area (SSA) decreased as temperature increased [18]. Additionally, it was noted that the electron transfer capability of biochar improved with increasing pyrolysis temperature [22]. The pyrolysis temperature had an important effect on the surface area and pore volumes of the biochar [23]. Surface area and pore volumes are significantly increase in the pyrolysis temperature from 400 ºC to 600 ºC [23].

It was suggested that biochar can be used as an effective additive to overcome the issues related to the anaerobic digestion process. Biochar can affectively accelerate the start-up reaction, increase the process stability and increase the methane productivity also.

2.5.1 Increase the Process Stability

Stability of anaerobic digestion process is essential for efficient biogas production. Stability of the anaerobic digestion process is restricted by the inhibition of volatile fatty acids (VFA) and ammonia[24]. Biochar supports the growth of methanogenic microbes, which break down nitrogen-rich materials. Lower ammonia levels improve the AD process, enhancing the breakdown of organic matter and increasing methane production. As a result, the overall efficiency and effectiveness of the anaerobic digestion process are improved [24] . As shown in Table 3, in 2016, Lü *et al.* have conducted an experiment by using three different sizes of biochar particles under the double inhibition risk from both ammonium and acids. If there is a risk with double inhibition the experiment proved that the biochar can increase the methane yield and reduced the lag phase by increasing the stability of the process.

Table 3 Methanogenesis Lag Phase Reduction Percentage and Methane Production Rate of Different Particle Size of Biochar [24]

Size of the Biochar Particles	**Methanogenesis Lag Phase Reduction Percentage**	**Increased Methane Production Rate**
2-5 mm	23.9 %	47.1 %
0.5-1 mm	23.8 %	23.5 %
75-150 µm	5.9 %	44.1 %

Methane production rate increased with the addition of biochar compared to the biocharfree conditions. Even with the high ammonium concentration in the process, the lag phase is reduced when adding the biochar into the system. According to the Table 3, compared to biochar-free conditions, the methanogenic lag phase was significantly reduced by 23.9% and 23.8% for biochar particle sizes of 2-5 mm and 0.5-1 mm, respectively, in environments with high ammonium concentrations. For smaller particle sizes, such as 75-150 µm, the reduction in the lag phase was slightly lower at 5.9%. This experiment was conducted under high ammonia concentration conditions. Therefore, Lü *et al.*(2016) proved that biochar can facilitate the methanization even under high ammonium stress. Similarly, in 2006, Shen et.al have found that, with the addition of two types of biochar (pine biochar and white oak biochar), free ammonia inhibition can be reduced by up to 10.5%. In this study also, it was reported that during the mesophilic and thermophilic AD, methane production is enhanced.

By increasing alkalinity, the process stability can be enhanced with addition of biochar [17]. By using biochar, Ammonium or ammonia toxicity can be overcome and the process stability is enhanced.

2.5.2 Accelerate the Start-up Reaction

Biochar has a high potential to accelerate the startup reaction of the anaerobic digestion process by reducing the lag phase of the reactions. Reduction of lag phase indicates that the microorganisms adapted more rapidly to their environment in the presence of biochar. Therefore, the startup time for methane production is shorter and this accelerates the entire anaerobic digestion process. In 2016, Lü et al. experimented with the behavior of the lag phase under different ammonium levels. The treatment methods and results of the experiment are shown in Table 4.

Table 4 Lag phase of Different Treatment under Ammonium Stress Level [24]

Treatment	**Treatment Method**	**Total Ammonium Level (g-N/L)**	**Lag Phase (days)**
N1	Without biochar	0.26	23.46 ± 0.24
N1CM	With the medium-sized biochar	0.26	16.33 ± 0.18
N3	Without biochar	3.5	30.46 ± 0.70
N3CM	With the medium-sized biochar	3.5	26.5 ± 0.64
N7	Without biochar	7	63.51 ± 2.68
N7CM	With the medium-sized biochar	7	48.39 ± 2.86
N7CL	With the large-sized biochar	7	48.33 ± 2.68
N7CS	With the small-sized biochar	7	59.77 ± 1.78

Table 4 shows that the treatment methods conducted without biochar exhibit higher lag phases comparing to those with biochar addition. Even with the highest ammonium concentration which 7 g-N/L, the lag phase was reduced from 63.51 days (without biochar) to 48.39 days with medium-sized biochar, 48.33 days with large-sized biochar, and 59.77 days with small-sized biochar. At an ammonia concentration of 3.5 g-N/L, the lag phase was reduced by four days when medium-sized biochar was used. With a low ammonia concentration (0.26 g-N/L), the addition of biochar reduced the lag phase from 23 days to 16 days. The experimental results from Lü et al. (2016) demonstrated that the addition of biochar significantly reduces the lag phase across various ammonia concentrations. According to the experimental data presented in Table 4, this observation is clearly evident also. This lag phase reduction accelerates the startup reaction of the biogas production process. Consequently, biochar can effectively accelerate the startup reaction by reducing the lag phase of the anaerobic digestion process, even under ammonia-stressed conditions [24]. If biochar can reduce the lag phase under such stressed conditions, it has high potential to enhance the startup reaction in normal conditions.

Further, Feijoo, Soto and Lema, (1995) was conducted the experiment to demonstrate the effectiveness of biochar addition at a high concentrations of total solids [13]. Increasing the high total solids content from 10 to 30% causes to decrease peak methane yield by around 60% [13]. Feijoo, Soto and Lema, (1995) was reported that with the addition of biochar, the lag phase was reduced by 17%, 27% and 41 at total solids contents of 5%, 10% and 20%, respectively. According to the experimental results of this study, biochar has a ability of reduce the lag phases of AD process even with the high total solid concentrations. Further in 2007 Qin et al. have researched and reported that all biochar treatments shortened the lag phase from 1.83 days to 0.9 days[25]. In 2016, Sunyoto *et al.*, also proved that with the addition of biochar the lag phases are shortened by 36.0% in H_2 reactor and 41.0% in methane reactor [26]. According to these results, biochar has a great potential of accelerating the start-up of AD by reducing the lag phase.

2.5.3 Increase the Methane Productivity

Numerous studies have demonstrated that the addition of biochar significantly enhances methane production rate, yield, and overall quantity. For an example, Lü et al.(2016) found that metahne production rate was significantly increased by 47.1%, 23.5% and 44.1% for biochar particle sizes of 2-5 mm, 0.5-1 mm and 75-150 µm, respectively, in environments with high ammonium concentrations [24]. Methane production is improving due to the surface oxygen-containing functional groups and graphitization degree of biochar [27]. But the methane yield varies with the particle size of the biochar. Figure 4 demonstrates that the Cumulative methane yield variation with different types of biochar.

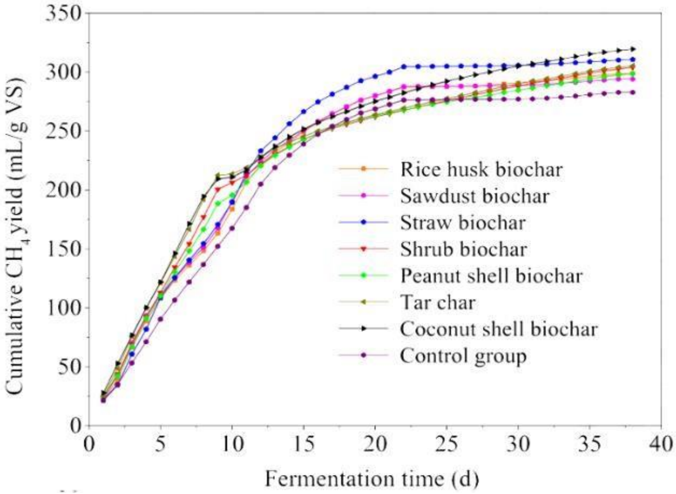

Figure 4 Effect of Biochar on Methane Yields [28]

The control group (without addition of biochar), exhibits the lowest cumulative methane yield [27]. Further, researchers indicates that methane yield also depends on biochar dosage. Shen *et al.*, have found that excessive biochar dosage can result in a lower methane yield [27],[29]. Methanoculleus, Figure 5 shows the variation in cumulative methane yield with different biochar dosages.

Figure 5 clearly demonstrates that a high dosage (4.0%) of biochar results in a lower methane yield, even compared to the control group. In the intermediate stages in AD process the VFAs are produced and these VFAs converted into methane. When using high amount of biochar dosage, produced VFAs are decreased due to biochar's adsorption capacity. Therefore, methane production is reduced because there aren't enough VFAs to produce methane with the high dosage of biochar. Therefore, the dose of biochar should be carefully controlled to obtain high yields of methane production. Furthermore, it was found that adding biochar to food waste improved the methane production rate by 23.0% to 41.6% [25]. In 2020, Zhang et al. demonstrated that using wood pallet biochar increased methane yield by 18% [28].

2.5.4 Mechanism of Biochar in Anaerobic Digestion Process

The biogas enhancing mechanism of AD is achieved through the major four functionalities of biochar. These are pH buffering, functional microbes enriching, inhibitors adsorption and DIET accelerating [30], [3]. Figure 8 shows that the conceptual diagram of the AD enhancing mechanism of biochar.

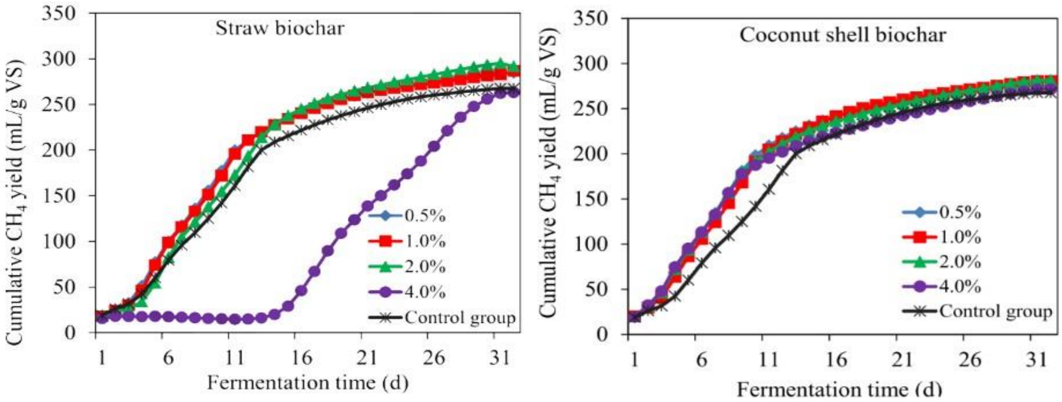

Figure 5 Cumulative Methane Yield a) Straw biochar and b) Coconut shell biochar with different Biochar Dosage [28]

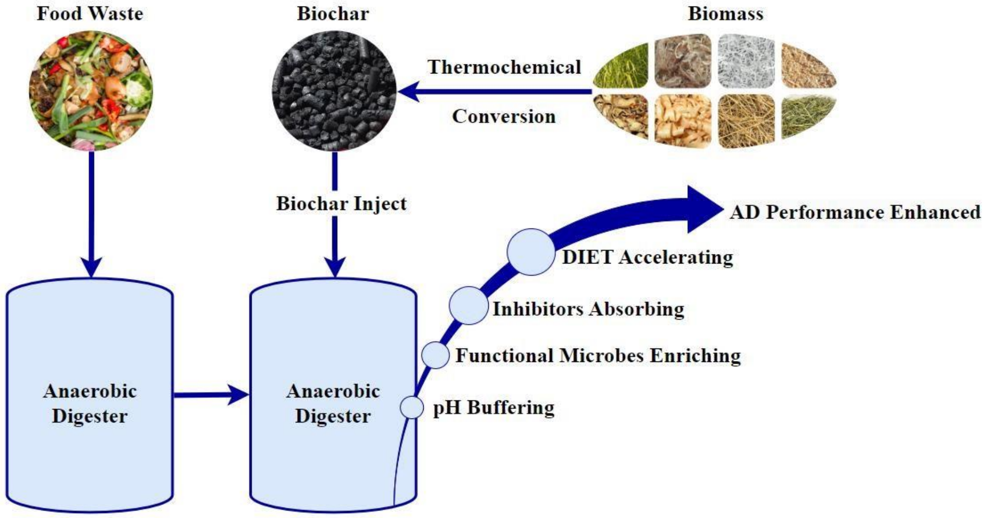

Figure 6 Concept Diagram of the Mechanisms of Biochar enhancing AD [3]

- **pH Buffering**

pH is one of the major factor that affects to the efficiency of AD process [7],[3],[4]. In intermediate stages of anaerobic digestion process VFAs are generated. In 2017, Li *et al.*, reported that the accumulation of volatile fatty acids (VFAs) may be the major cause of methane production inhibition[31]. Food waste with a high loading rate and a low C:N ratio has the potential to rapidly accumulate volatile fatty acids (VFAs)[8], [32]. The buffering capacity of the AD system must be sufficient to neutralize excessive acids and prevent the accumulation of volatile fatty acids (VFAs). Inadequate buffering capacity can lead to a decrease in methane production rates and a drop in pH below the methanogens' tolerance level [31]. Furthermore, Li et al. (2017) reported that biochar improved the buffer capacity due to its ash-inorganic and organic alkali functional groups, which effectively neutralized VFAs and prevented rapid pH decline [31]. Therefore, with the addition of biochar, the VFAs accumulation rate can be reduced and create a suitable environment for methanogens to transform VFAs to methane. Figure 7 clearly shows that in the digesters without biochar, methanogenic activity was inhibited at a pH lower than 6.6.

According to the Figure 7, it can be clearly observed that when increasing the VFA concentration, the pH value is decreased in the digestion time of 6-12 days. The concentration of VFAs is higher in the control group compared to the group with biochar addition. Therefore, it can be concluded that biochar has a significant pH buffering capacity.

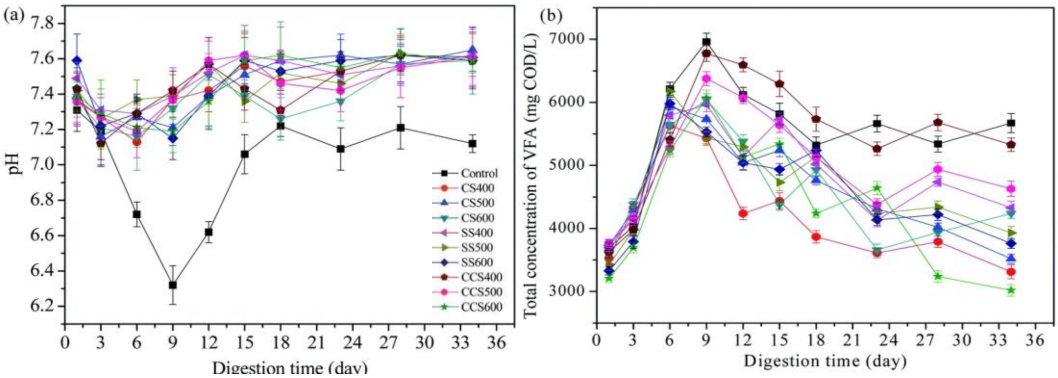

Figure 7 Changes in the pH (a), total VFA (b) with the Different Types of Biochar [3]

- **Functional Microbes Enriching**

Biochar has an ability to enhance the microbial activities for methane production. Addition of biochar facilitate the growth of attached microbes and as a result, methanogenic loss in AD process can be eliminated [3]. High SSA and abundant porosity of biochar affects to the microbial enrichment and colonization [22]. The dominant methanogenic species may change as a result of the microbial colonization, becoming more resistant to substrateinduced inhibition [33]. Therefore, enriching functional microbes is more essential for an efficient AD process. In 2020, Tang et al. also reported that due to the high surface area of biochar, it may affect microbial enrichment and colonization [3]. Biochar may promote the growth of biofilms and lead to microbial enrichment for the enhancement of AD [32].

According to Huggins *et al.*, 2016, biochar has pore sizes ranging from 1 to 40 μm, capable of accommodating 2–10 methanogenic cells per pore [34], [32]. Hence, selecting biochar with an optimal pore size distribution is crucial for promoting biofilm formation [32]. Then this may cause to enhance COD removal by 53.3%. Additionally, H_2 production was enhanced and the lag phase was shortened by 4 days with the addition of biochar [33].

The specific bacteria, like Syntrophomonas and Syntrophobacter, are necessary for efficiently breaking down VFAs, preventing their accumulation and improve the methane production of AD process [35]. In 2016, Cai *et al* indicated that these bacteria thrive better in the presence of biochar, leading to a more efficient degradation process [35]. Moreover, Masebinu *et al.*, 2019 reported that biochar promotes the creation of microbial biofilms. The microbial biofilms support the colonization of acidogens, acetogens and methanogens that helps to achieve COD reduction in 69%. With biochar-enhanced biofilms, the AD process reached an average methane concentration of 60% and produced methane at a rate close to the theoretical maximum, indicating high efficiency [33]. When considering the characteristics of biochar such as; nutrient levels, adsorption capacity, pH, surface characteristics and conductivity, the main factors that influenced how biochar affected microbial enrichment in short-term batch AD were its nutrient levels, adsorption capacity, pH, and surface characteristics. These factors were more important than the conductivity of the biochar in determining its effect. [3].

- **Inhibitors Adsorption**

One of the key benefits of biochar in enhancing AD performance is its ability to adsorb inhibitors [32]. Among the properties of biochar, including surface area, functional groups and pore volume, functional groups are the primarily influence the adsorption of inhibitors [3]. The OH and COOH groups present in biochar facilitate π-π interactions for adsorption through their aromatic structures [32]. It was reported that the modified biochar's (MeOHBC) oxygen functional groups could be the main factor influencing the π-π interactions [36]. In 2021, Kumar *et al.* demonstrated that the sorption of H_2S may facilitates by the presence of carboxylic and hydroxide radical groups in biochar [32]. In 2001 Bagreev, Bandosz and Locke, found that the pore structure has an abaility for adsorbing chemical compounds including ammonium, phosphate, heavy metals, nitrate, CO_2 , pesticides, heavy metals, and nitrite [37]. Figure 8 shows the adsorption capacity of total ammonia nitrogen and free ammonia nitrogen contents. These two values significantly decrease with usage of biochar. According to the results, the biochar could effectively reduce the ammonia inhibition and make the suitable environment for methanogenesis process.

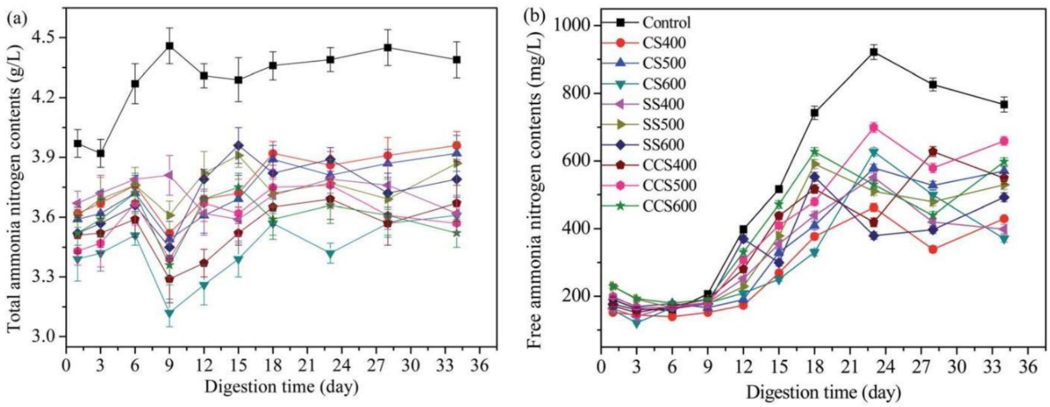

Figure 8 Course of total ammonia nitrogen (a) and free ammonia nitrogen (b) [3]

Not only ammonia and VFA inhibit the AD process, but it is also inhibited by organic toxicants (chlorophenols, halogenated aliphatic and long chain fatty acids), inorganic toxicants (ammonia, sulfide and heavy metals) and in particular, nanomaterials [38]. Biochar has a capacity to absorb these inhibitors also[37]. The functional groups found in biochar are common to many other carbon-based adsorbents [32]. Therefore, this may prove that the biochar has an ability to absorb inhibitors.

- **DIET Acceleration**

Biochar has an excellent ability to transfer the electrons due to its electrochemical functional groups and π-electron distribution [22]. Direct interspecies electron transfer (DIET) is a newly discovered process that speeds up the conversion of certain organic compounds into methane (CH_4) by allowing microbes to share electrons directly [33]. According to Chen et al. (2014), DIET between microorganisms is known to be enhanced [39]. The flow of electrons between bacteria and methanogens speeds up by the functional groups such as hydroquinone and quinone. Furthermore, extracellular electron transfer with biochar and electroactive microorganisms is enhanced by the presence of biological electron components like cytochromes [22].

Due to the abundance of certain microorganisms (Anaerolineaceae and Methanosaeta) engaged in DIET, according to an electron stoichiometry investigation, 58.7% of the electrons released during acetate oxidation may be recovered by biochar [40]. Biochar improves DIET kinetics between methanogens and their partners [3]. And also, DIET can improve the methanogenesis phase significantly for a well-functioning acidogenesis process [33]. Through the cooperative breakdown of butyrate and acetate, Li *et al.* found that biochar enhanced the exchange of electrons between bacteria and methanogens attached to biochar, most likely through DIET [31].

3 Conclusion

Biochar has a great potential to enhance the biogas production from anaerobic digestion process. The properties of biochar depend on the feedstock quality and the pyrolysis process parameters. The application of biochar in AD process serves four major functions such as; pH buffering, microbial function enrichment, inhibitors absorbing and DIET accelerating. This review explores the impact of biochar in biogas production from anaerobic digestion of food waste with the identification of the properties of biochar also. It was proved that with the addition of biochar, AD process is enhanced by increasing the methane production rate and methane yield, adsorbing inhibitors, mitigating the ammonia and VFAs inhibition. Overall, biochar proves to be a valuable tool in maximizing the potential of anaerobic digestion systems for sustainable energy production.

4 Research Gaps and Future Trends

There are some barriers with the usage of biochar in AD process and its commercial scaling up. The most of the studies are carried out in lab scale by using reactors ranging from 0.11.8 L volumes. And also, relationship between properties of biochar and AD performance are not fully understood. Therefore, more extensive researches need to be identified the relationship between properties of biochar and the AD performances. Furthermore, with the high biochar dosage the methane yield is reduced. Therefore, optimum amount of the biochar dosage needs to be identified relevant to the different biochar.

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